FABRICATION OF UNIAXIAL FILAMENT-REINFORCED EPOXY TUBES FOR STRUCTURAL APPLICATIONS

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Presented at the 14th National SAMPE Symposium

Cocoa Beach, Florida
November 5-7, 1968

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ABSTRACT

A process has been developed for fabricating uniaxial filament-reinforced epoxy tubes. The process utilizes hand layup techniques, a Teflon mandrel, and a heat-shrinkable Teflon sleeve. At the present, over 40 tubes of boron-epoxy and S-glass-epoxy have been fabricated using the process reported herein. The tubes are essentially void free, exhibit less dimensional variation than the tolerances set for commercially available extruded aluminum tubing, and display a smooth surface finish. Short sections of both types of tubing have been subjected to axial compression tests. The boron-epoxy and S-glass-epoxy tubes exhibited average strengths of 309 ksi (2.13 GN/m^2) and 207 ksi (1.43 GN/m^2), respectively.

INTRODUCTION

During the past few years considerable interest has been displayed in the potential application of filament-reinforced composite materials to aerospace structures. Previous studies, as pointed out in reference 1, indicate that for certain structural components the largest weight savings or highest strengths are possible if all of the reinforcing filaments are alined in the direction of the applied load. One such application is a column loaded in axial compression. In order to obtain information on such members, the NASA Langley Research Center initiated an investigation to study the compressive behavior of uniaxial filament-reinforced epoxy tubes.

The first phase of the investigation consisted of developing a method for fabricating tubes of suitable quality for use in the study. Nominal 0.5 in. (13 mm) diameter tubes of boron-epoxy and S-glass-epoxy were selected for use in the investigation due to factors such as existing fabrication and test equipment at the Langley Research Center, and the range of length-to-diameter ratios to be investigated. Based on the size requirements, 0.5 in. (13 mm) diameter and lengths up to 40 in. (1.0 m), conventional filament winding did not appear suited for fabricating the required uniaxial filament-reinforced epoxy tubes. Helically wound tubes of the required size could have been fabricated using the filament winding process. However, results presented in reference 2 suggest that a 5^{o} helix angle would reduce the compressive strength by more than 40 percent compared to the strength of a uniaxial filament-reinforced tube. Therefore, a hand layup process that utilizes unidirectional filament-reinforced epoxy tape was developed for fabricating the required tubes.

The purpose of this paper is to describe the process utilized to fabricate the tubes which are being used in the investigation. In addition, data on the dimensional variation and compressive strength of tubes thus fabricated are included.

The units used for physical quantities defined in this paper are given in both the U.S. Customary Units and in the International System of Units (SI). Conversion factors pertinent to the present investigation are presented in the appendix and in reference 3.

FABRICATION PROCESS

The flow diagram of the process for fabricating uniaxial filament-reinforced tubes is shown in figure 1. For purpose of explanation, the process is divided into five steps. The first step consists of cutting and alining strips of preimpregnated filaments on a polytetrafluorethylene (Teflon) rod which serves as a mandrel. Care is taken to aline the filaments parallel to the longitudinal axis of the mandrel. The width of each strip is approximately equal to the circumference of the tube plus 1/16 in. (1.6 mm) which is allowed for overlap in each ply. Strips or plies are added until the required wall thickness is obtained. The splice or overlap areas in the various plies are spaced around the circumference of the mandrel such that uniform wall thickness is approached.

In the second step, a heat-shrinkable Teflon sleeve is slipped over the mandrel and preimpregnated filaments. The diameter of the sleeve should be just large enough to permit the sleeve to be slipped over the preimpregnated filaments without damaging the outer ply of filaments.

The third step consists of heating the Teflon sleeve with air from an electric heat gun. Shrinkage occurs completely at exposure to 350^{o} F (450^{o} K) with partial shrinkage occurring at exposure as low as 200^{o} F (366^{o} K). As the sleeve shrinks tightly on the preimpregnated filaments, air entrapped between the plies of preimpregnated filaments is squeezed out the end of the sleeve. In addition, the Teflon sleeve serves as a mold which forms a smooth outer surface on the filament-reinforced tube.

Next, step four, the assembly (mandrel, preimpregnated filaments, and heat-shrinkable sleeve) is inserted in a steel tube which prevents the mandrel from sagging while the epoxy resin is cured at elevated temperature. The steel tube and assembly are heated in a circulating-air oven in order to cure the epoxy.

Step five consists of removing the assembly from the steel tube, peeling the heat-shrinkable sleeve from the outer surface of the filament-reinforced tube, and extracting the mandrel. Before testing, each end of the tube is machined flat, square, and parallel.

Additional details on the first three steps in the fabrication process are shown in figures 2 through 4. Figure 2 shows the first step in the fabrication process. Included in the photograph are a mandrel support jig, 0.5 in. (13 mm) diameter Teflon mandrel, and a strip of preimpregnated boron filaments. Sagging of the mandrel was prevented by applying tension with the aid of nuts on the threaded ends of the mandrel.

Figure 3 shows the second step in the fabrication process which consists of slipping the heat-shrinkable Teflon sleeve over the preimpregnated filaments and mandrel.

In figure 4, which shows the third step in the fabrication process, approximately one-half of the shrinkable sleeve has been heated. After heating, the sleeve fits tightly on the mandrel and preimpregnated filaments. Typical sections of boron-epoxy and S-glass-epoxy tubes are shown in figure 5.

INSPECTION AND TEST

Tube Inspection

For the tubes reported in this study, inspection consisted of a careful visual examination for surface defects, measurement of the outside diameter and wall thickness at various stations along the tube, and, for some tubes, a detailed study of the cross section utilizing photomicrographs. No attempt was made to utilize radiographic or ultrasonic inspection techniques. The tubes were visually examined for filament misalinement, surface defects, and curvature in the axial direction. Straightness was further checked by rolling the tubes on a flat surface. Wall thickness was measured at four points around the circumference at three stations along the length of the tube. At least two outside-diameter measurements were taken at each of three stations along the length of the tube. Photomicrographs of tube cross sections were examined for voids.

Compression Test

Short sections of tube, 1.5 in. to 3.0 in. (38 to 76 mm) long, were tested in axial compression. Prior studies, such as the one reported in reference 4, have indicated that uniaxial filament-reinforced epoxy material fails at low stress levels in axial compression by "brooming" of the ends. To prevent "brooming," stainless-steel end plugs such as the one shown in figure 6 were bonded to each end of the tube with a room-temperature-curing epoxy resin. The diameter and thickness of

the end plugs were 1.0 in. and 0.25 in. (25 and 6 mm), respectively. The machined groove was 0.125 in. (3.2 mm) deep and wide enough to permit at least 0.010 in. (0.25 mm) clearance on the inside and outside of the tube. Prior to inserting the specimen into the end plug, the machined groove was filled with epoxy resin such that bonding and support were provided on both the inside and the outside surfaces of the tube.

The compression test setup is shown in figure 7. Prior to testing, the hydraulic testing machine platens were alined parallel to the end plugs to obtain uniform loading over the specimen ends. The specimen was loaded continuously at a strain rate of 0.001 per minute until failure. Strain and overall shortening were measured using strain gages and a linear direct-current differential transformer, respectively.

RESULTS AND DISCUSSION

Over 40 uniaxial filament-reinforced tubes of either boron-epoxy or S-glass-epoxy have been fabricated using the process reported herein. Fabricated lengths ranged from about 12 in. to 40 in. (0.3 to 1.0 m). Wall thickness for the boron-epoxy and S-glass-epoxy tubes ranged from about 0.015 in. to 0.065 in. (0.4 to 1.7 mm) and 0.015 in. to 0.10 in. (0.4 to 2.5 mm), respectively. Material properties and the cure cycle for each type of prepreg tape are listed in table I.

Inspection

Visual examination of the tubes indicated very smooth inner and outer surfaces, which were produced by the direct contact of the inner and outer plies of preimpregnated filament with Teflon surfaces (see fig. 5). Because of the smooth surfaces, outside-diameter and wall-thickness measurements were readily obtainable and strain gages were easily bonded to the outer surface of the tube.

The typical variation in outside diameter and wall thickness of a four-ply boron-epoxy tube are shown in figure 8. Measurements were taken at four locations around the circumference at each of three stations along the length of the tube. The maximum variation in outside diameter was 8 mils (0.2 mm); whereas, wall thickness varied 4 mils (0.1 mm). Similar variations were observed in S-glass-epoxy tubes and for other numbers of plies. According to ASTM Designation B221-67 (ref. 5), the permissible variation in outside diameter and wall thickness for an extruded aluminum tube of the size indicated in figure 8 is 20 mils and 10 mils (0.5 mm and 0.25 mm), respectively. The straightness tolerance listed in reference 5 was met by all tubes. Consequently, the dimensional variation in tubes fabricated using the process reported herein is less than the tolerances set for extruded aluminum tubing.

Cross-sectional views of a boron-epoxy tube and a S-glass-epoxy tube are shown in figure 9. The upper-left photograph illustrates the rather uniform filament spacing exhibited by most of the prepreg tape used in the investigation to date. Dark areas around filaments should not be mistaken

for voids in the composite. These dark areas represent portions of the specimen cross section that were inadvertently removed during the polishing operation. This kind of polishing problem is characteristic of materials that contain a very soft phase (resin) and an extremely hard phase (boron filament). The upper-right photograph in figure 9 shows a joint or splice area in a three-ply tube. The inner and outer ply are continuous; whereas, the middle ply is spliced or overlapped. The bottom photograph in figure 9 shows a cross-sectional view of a two-ply S-glass-epoxy tube. The cross section is free of voids but several resin-rich areas are present. Preliminary results from burnout tests substantiate the low void content of the S-glass-epoxy tubes. Based on the photomicrographs shown in figure 9, the fabrication process reported herein appears to yield essentially void-free composites.

Compression Test

A boron-epoxy tube and a S-glass-epoxy tube that have been failed in axial compression are shown in figures 10 and 11, respectively. The test data are plotted in figure 12. In the boron-epoxy tube, failure occurred by buckling or breaking of the boron filaments. Based on test data from four specimens, compressive strength for the boron-epoxy tubes ranged from 287 ksi to 324 ksi (1.98 to 2.23 GN/m^2) with an average of 309 ksi (2.13 GN/m^2). The filament stress at failure averaged approximately 618 ksi (4.26 GN/m^2) (see fig. 12). This is believed to be as high as any value of compressive filament strength previously obtained from specimens containing more than 40 percent filaments by volume and, in general, exceeds the values reported in the literature by at least 20 percent (see, for example, refs. 6 and 7).

In the S-glass-epoxy tubes failure also occurred by buckling or breaking of the reinforcing filaments (see fig. 11). Based on 17 tests, axial compressive strength for the S-glass-epoxy tubes ranged from 172 ksi to 236 ksi (1.18 to 1.63 GN/m^2) with an average of 207 ksi (1.43 GN/m^2). The average compressive stress in the glass filaments at failure was approximately 345 ksi (2.38 GN/m^2) or about 20 percent higher than the value reported in reference 8 for S-glass-epoxy laminates (see fig. 12).

Observation of the axial-compression test results indicate that boron-epoxy and S-glass-epoxy tubes fabricated, using the process reported herein, are of high quality. In addition, comparison of the filament stresses at failure with strengths previously reported by other investigators suggests that short tube specimens are useful in obtaining the compressive strength of unidirectional filament-reinforced composites.

CONCLUDING REMARKS

Based on the results obtained from a study on uniaxial filament-reinforced tubes, the following conclusions are drawn:

1. A relatively simple process has been developed for fabricating uniaxial filament-reinforced epoxy tubes.

2. Boron-epoxy and S-glass-epoxy tubes fabricated using the process reported herein are essentially void free, exhibit less dimensional variation than the tolerances set for extruded aluminum tubes, and display a smooth surface finish.

3. The average failure strengths of boron-epoxy and S-glass-epoxy tubes tested in axial compression was 309 ksi and 207 ksi (2.13 and 1.43 GN/m^2), respectively.

4. Higher filament compressive strengths were obtained in these short tube tests than have been heretofore reported with other types of test specimens containing more than 40 percent filaments by volume.

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APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 3). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Length	in.	0.0254	Meters (m)
Stress	ksi	6.895×10^6	Newtons per square meter (N/m^2)
Temperature	(^{O}F + 460)	5/9	Degrees Kelvin (^{O}K)

*Multiply value given in U.S. Customary Units by conversion factor to obtain equivalent value in SI Units.

Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
Milli (m)	10^{-3}
Giga (G)	10^{9}

TABLE I.- MATERIAL PROPERTIES OF PREPREG TAPES

Reinforcing filament	Boron	S-glass
Resin system	Epon* 1031/828/MNA/BDMA	XP-251S†
Resin content, percent by weight	29 ± 3	25 ± 3
Cloth backing	104 glass scrim	None
Nominal thickness per ply	0.005 in. - 0.006 in. (0.13 - 0.15 mm)	0.0075 in. (0.19 mm)
Cure cycle	1 hr at 180° F (356° K) plus 3 hr at 350° F (450° K)	12 hr at 300° F (422° K)

*Manufactured by Shell Chemical Co.
†Manufactured by Minnesota Mining and Manufacturing Co.

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John G. Davis, Jr., received a B.S. degree in mechanical engineering from North Carolina State University in 1962 and a M.S. degree from Virginia Polytechnic Institute in 1965. Since joining NASA in 1962, Mr. Davis has been engaged in research and development studies on materials and structural concepts for hypersonic aircraft and fiber-reinforced composites. Currently, Mr. Davis is conducting studies on boron, carbon, and glass fiber reinforced epoxy composites.

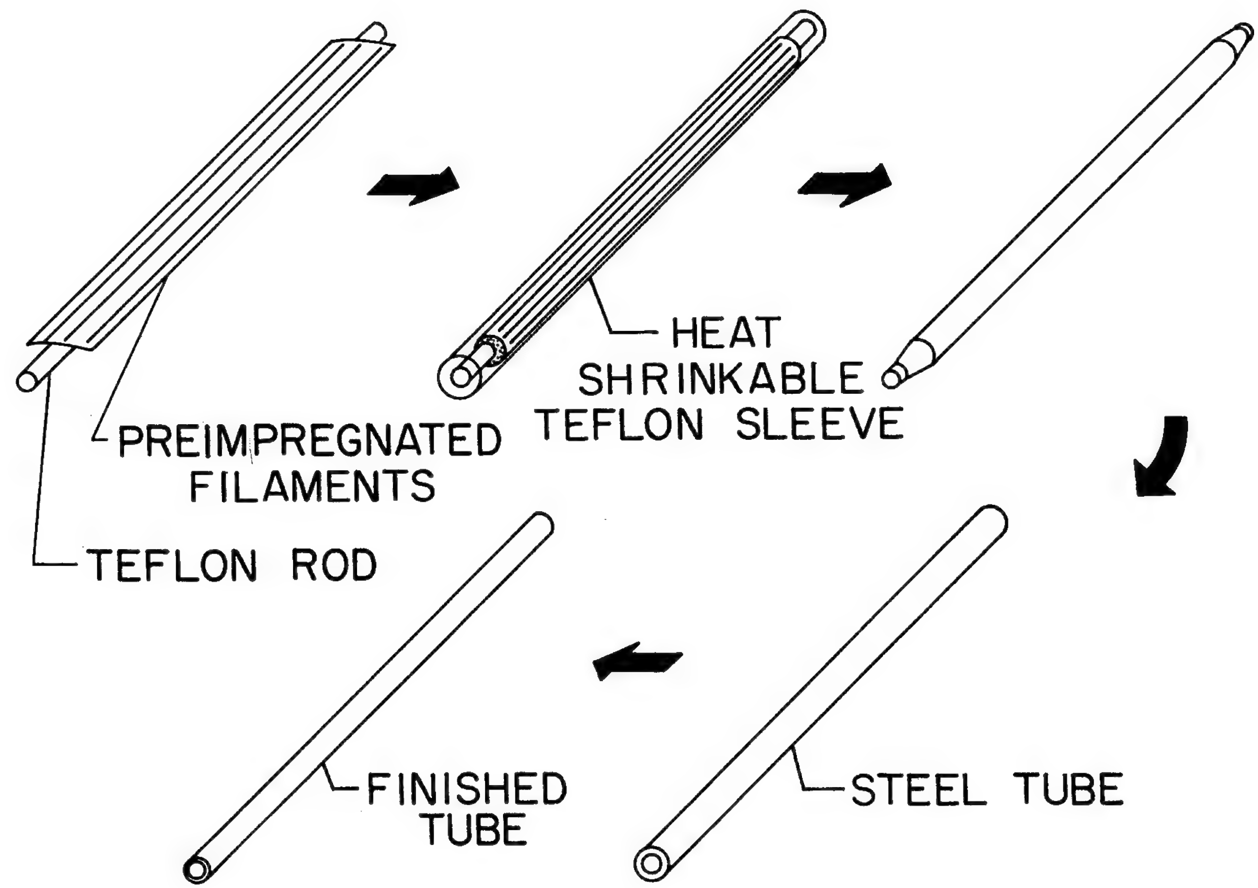

Figure 1.- Flow diagram of the process for fabricating uniaxial filament-reinforced epoxy tubes.

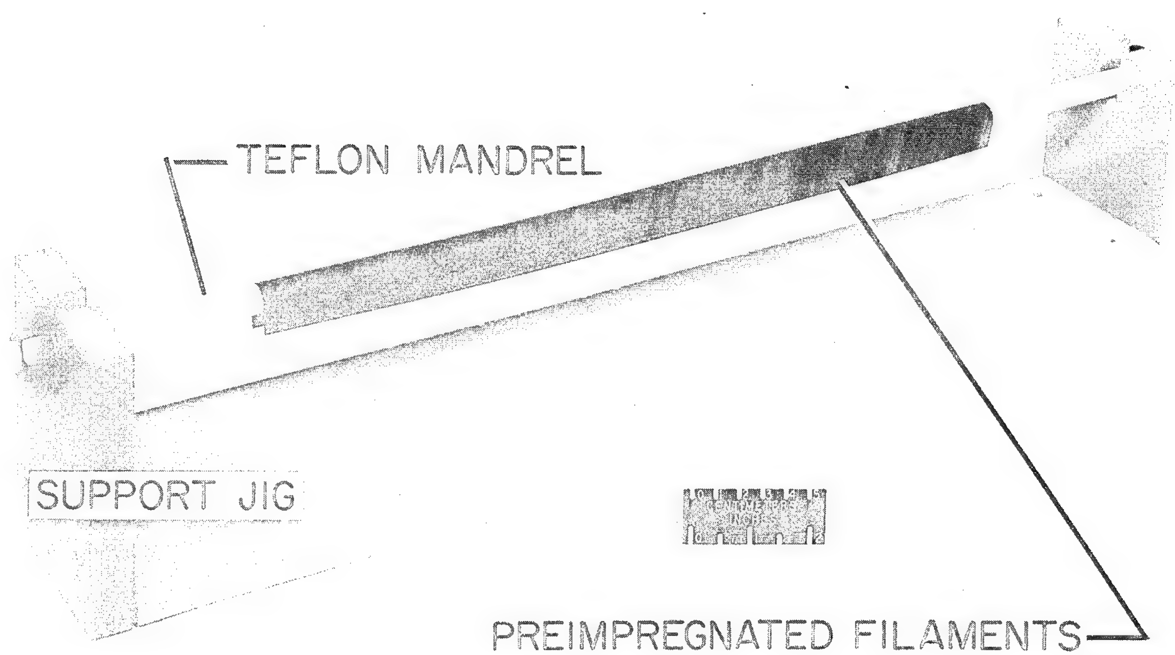

Figure 2.- Step 1 in fabrication process - strip of preimpregnated filaments alined on mandrel.

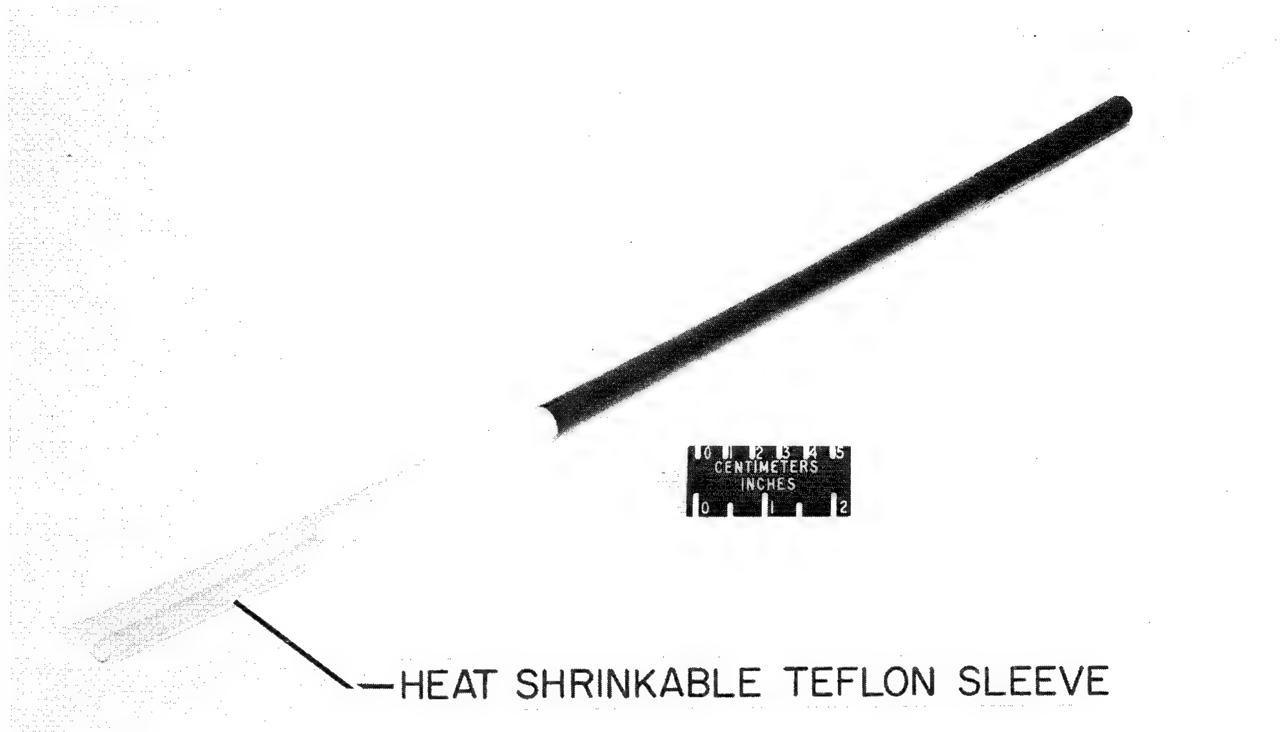

Figure 3.- Step 2 in fabrication process - heat-shrinkable Teflon sleeve slipped over preimpregnated filaments.

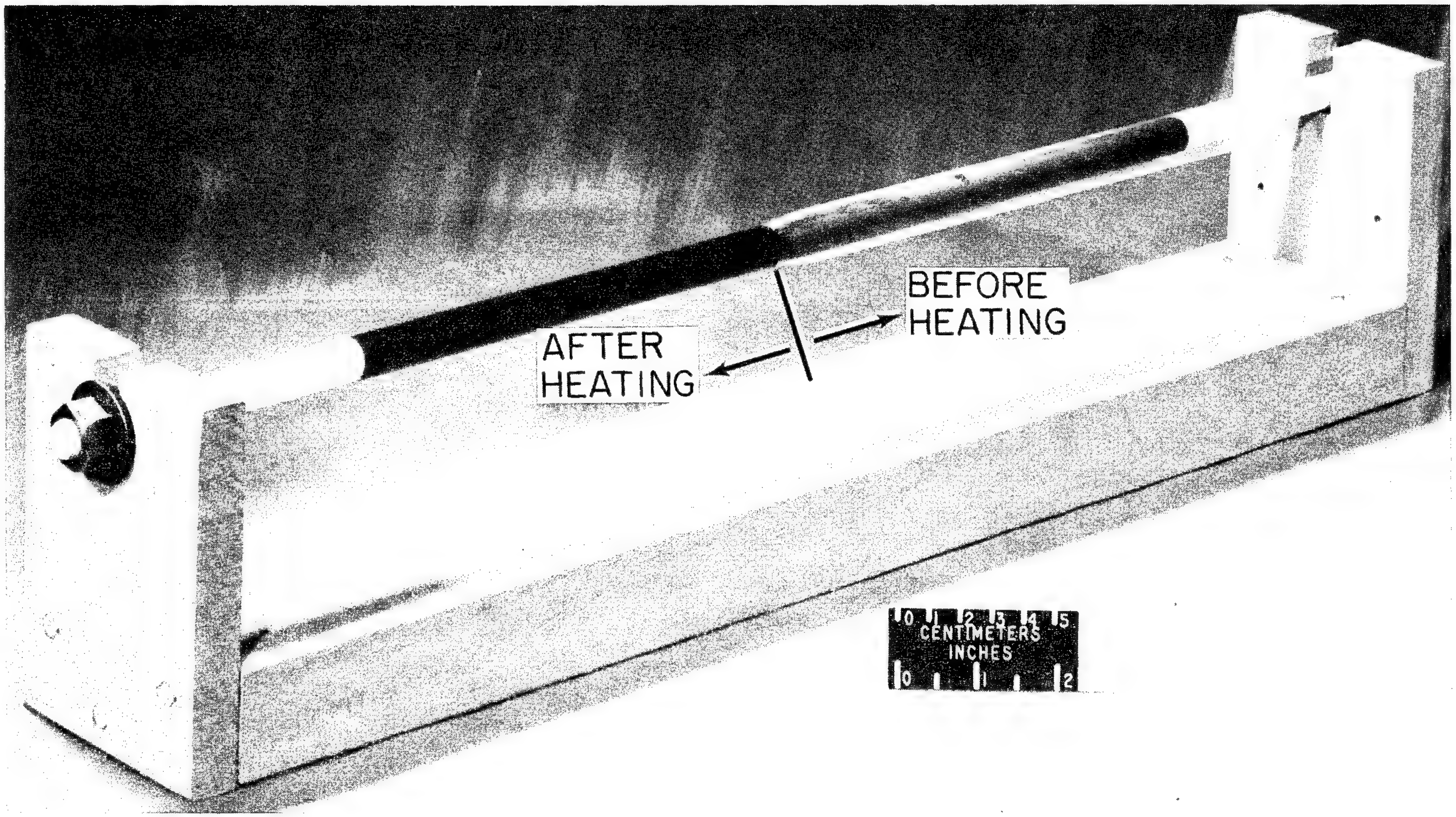

Figure 4.- Step 3 in fabrication process - shrinking Teflon sleeve on preimpregnated filaments.

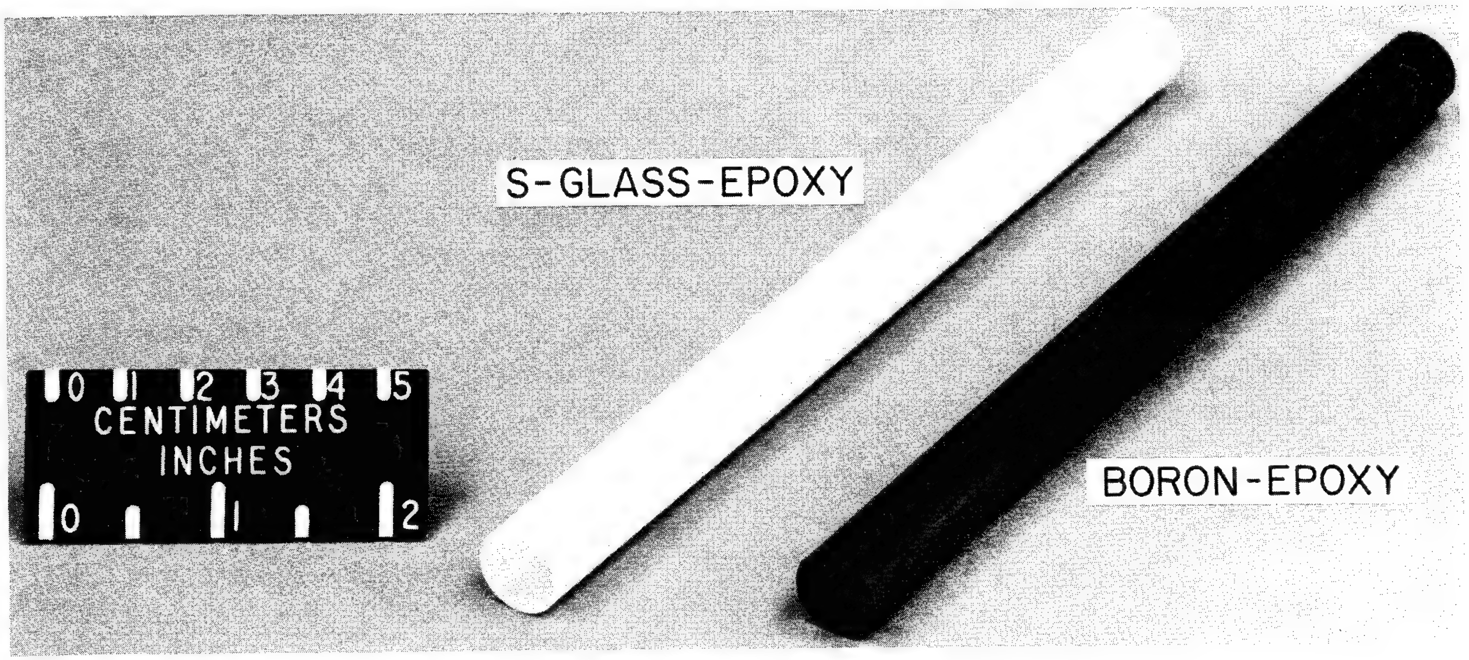

Figure 5.- Uniaxial filament-reinforced tubes.

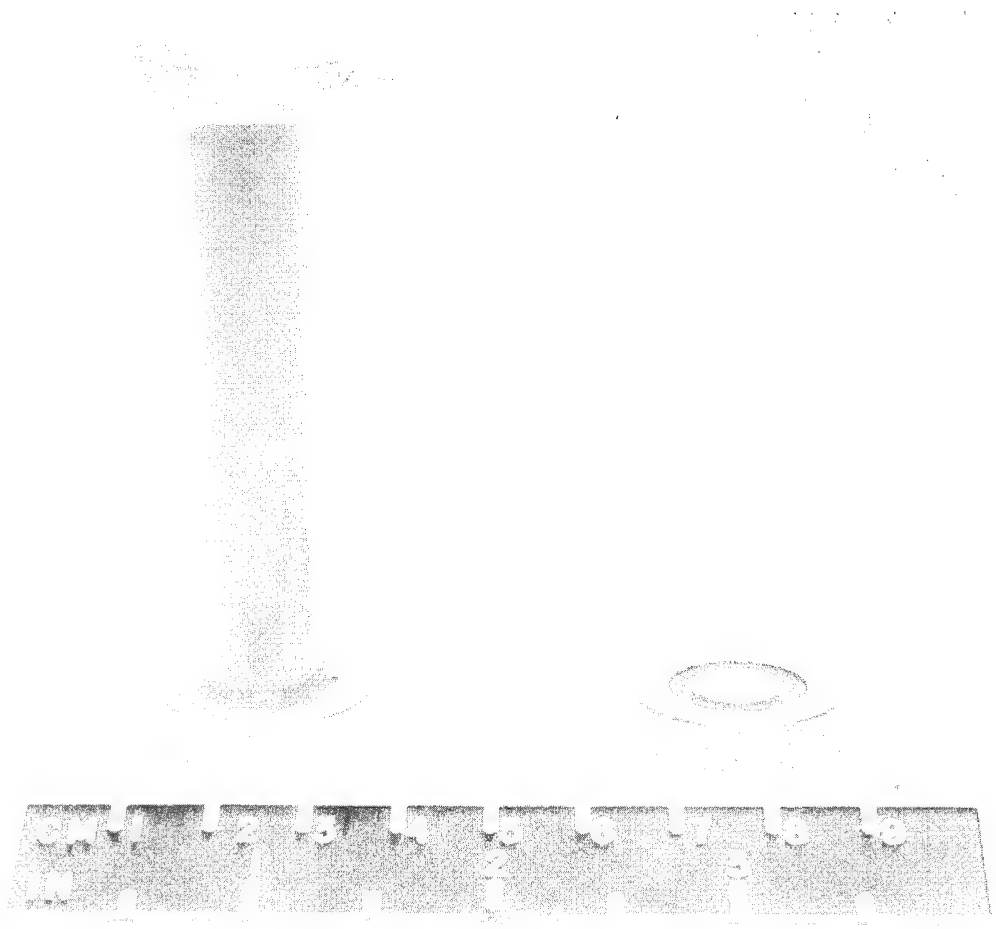

Figure 6.- Stainless-steel end plugs and specimen assembly for axial compression test.

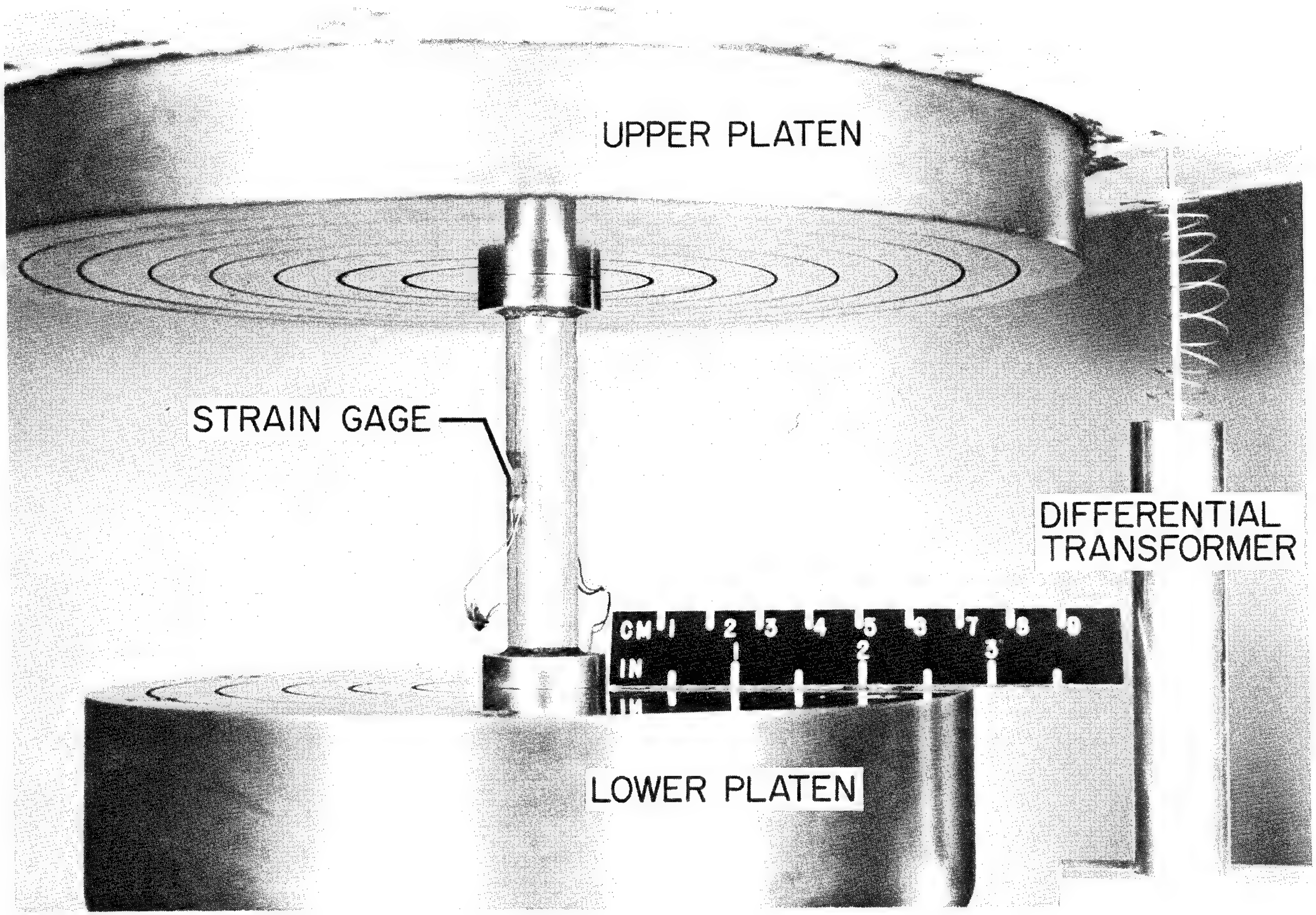

Figure 7.- Axial compression test setup.

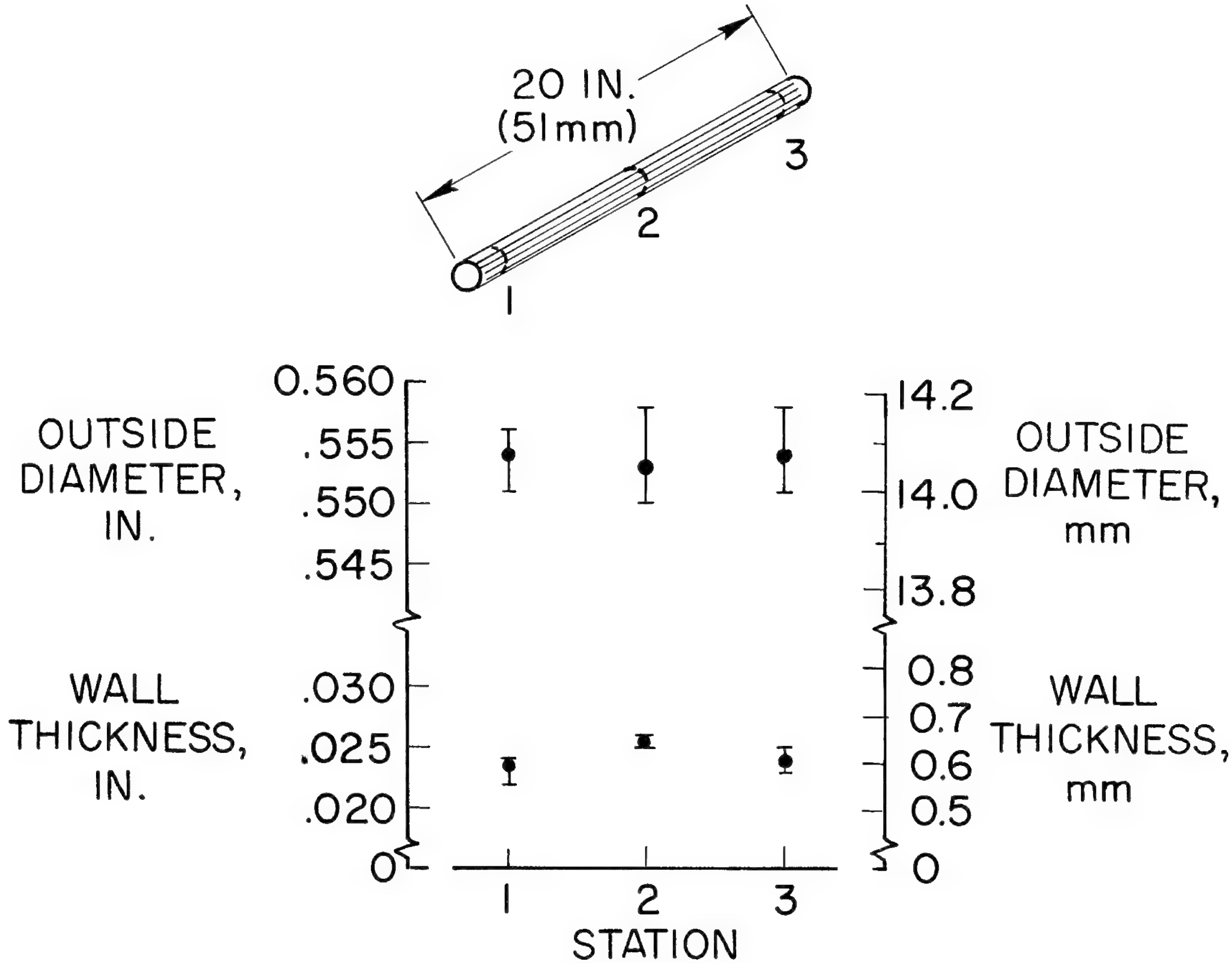

Figure 8.- Typical variation in outside diameter and wall thickness for a 4-ply boron-epoxy tube.

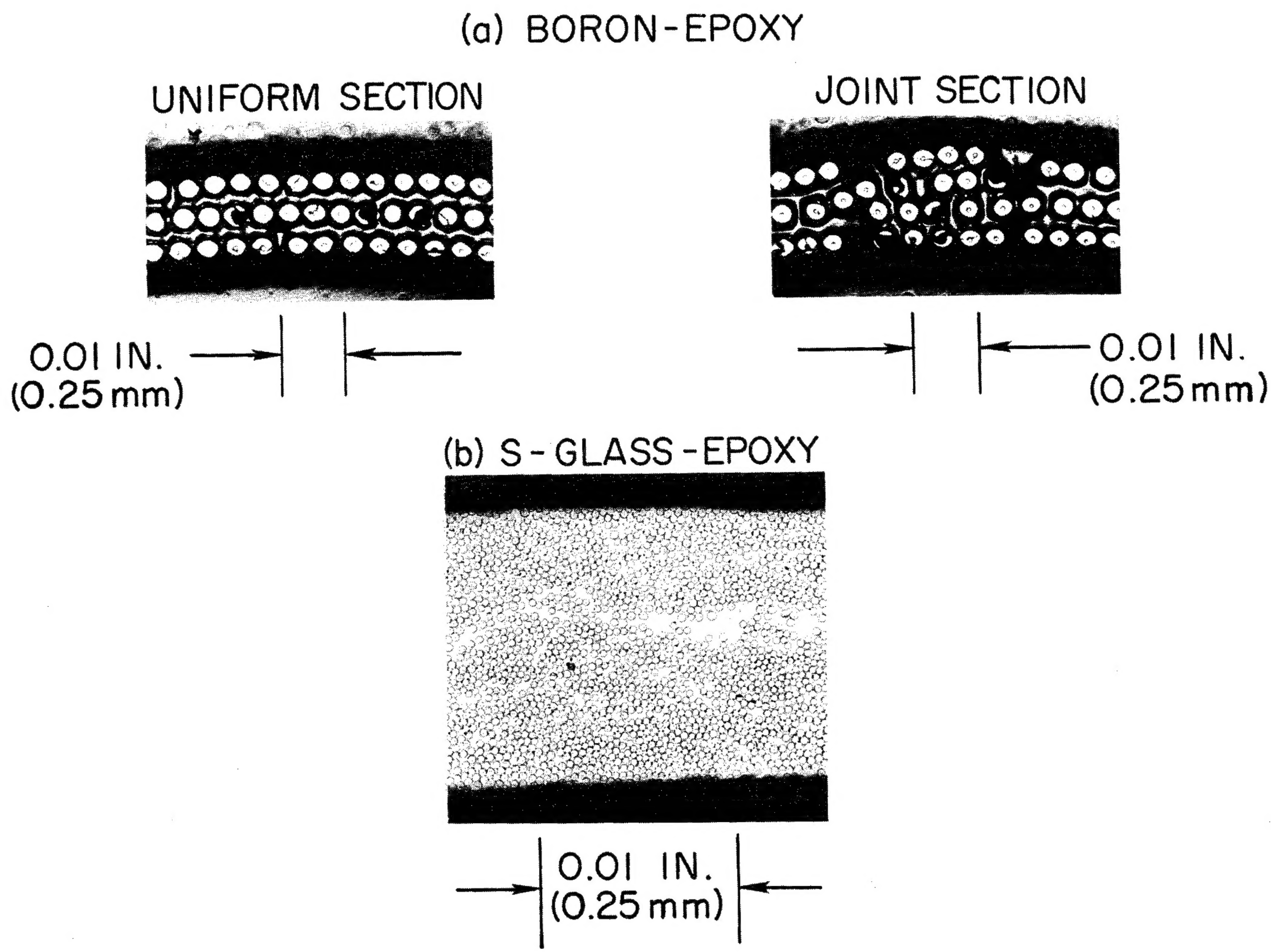

Figure 9.- Photomicrographs of tube cross sections.

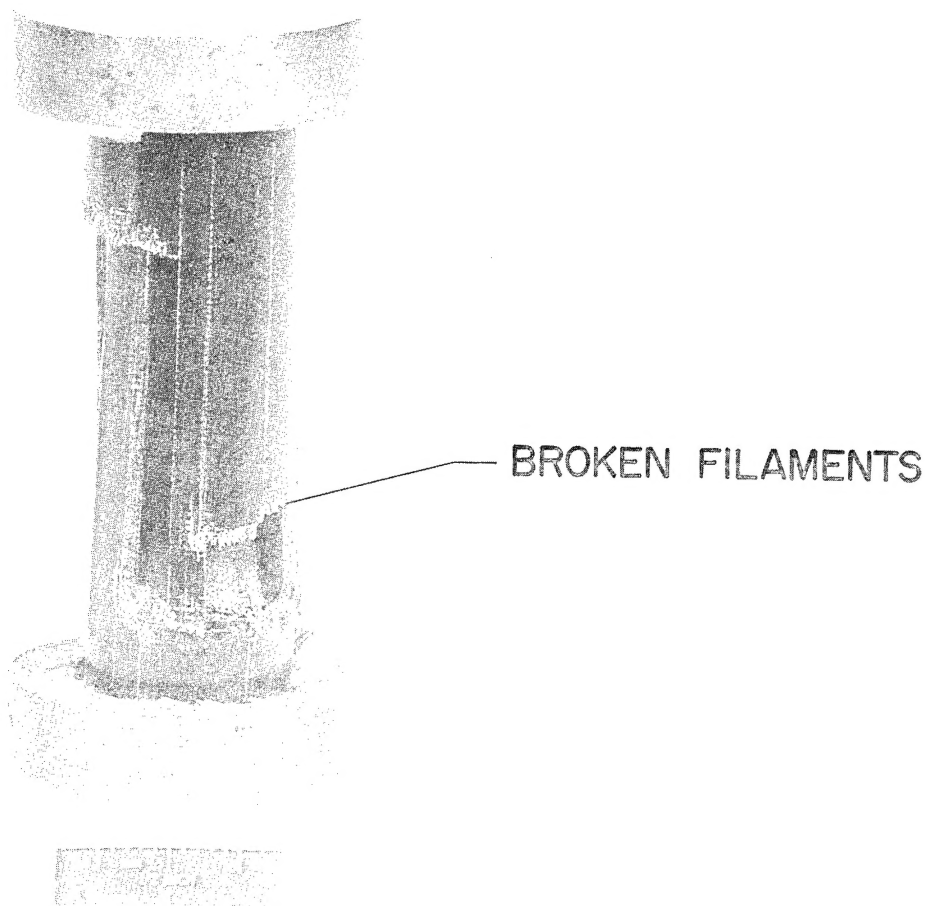

Figure 10.- Failed boron-epoxy tube.

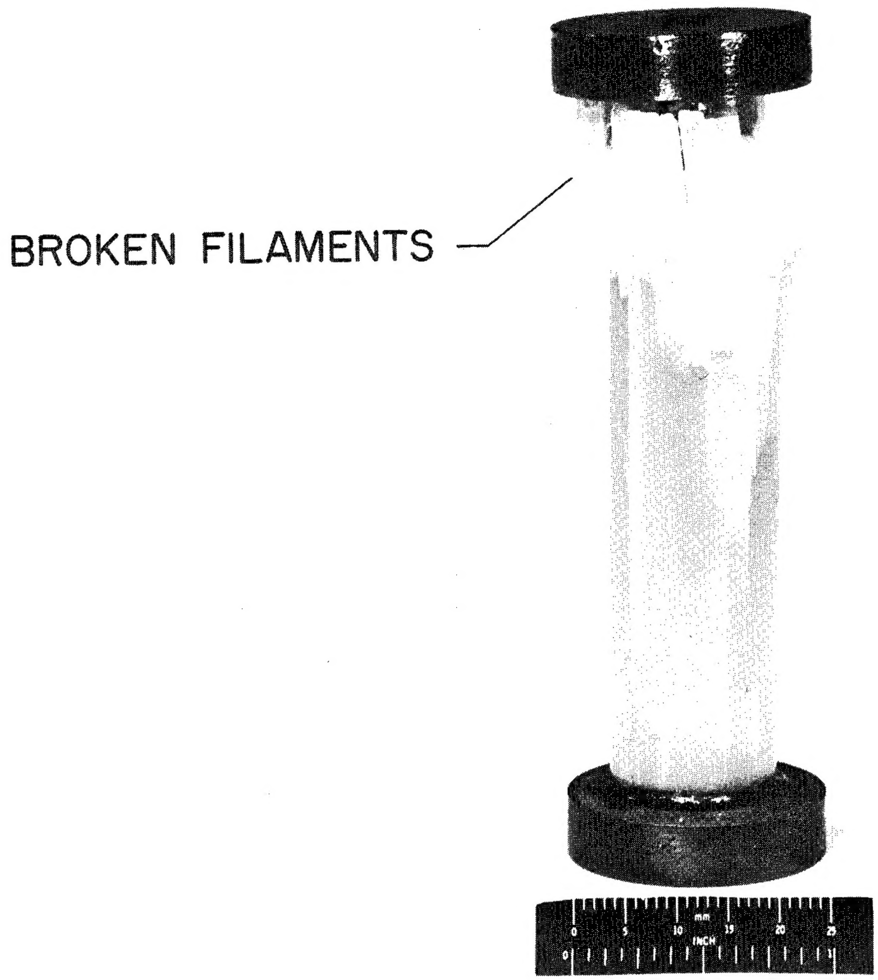

Figure 11.- Failed S-glass-epoxy tube.

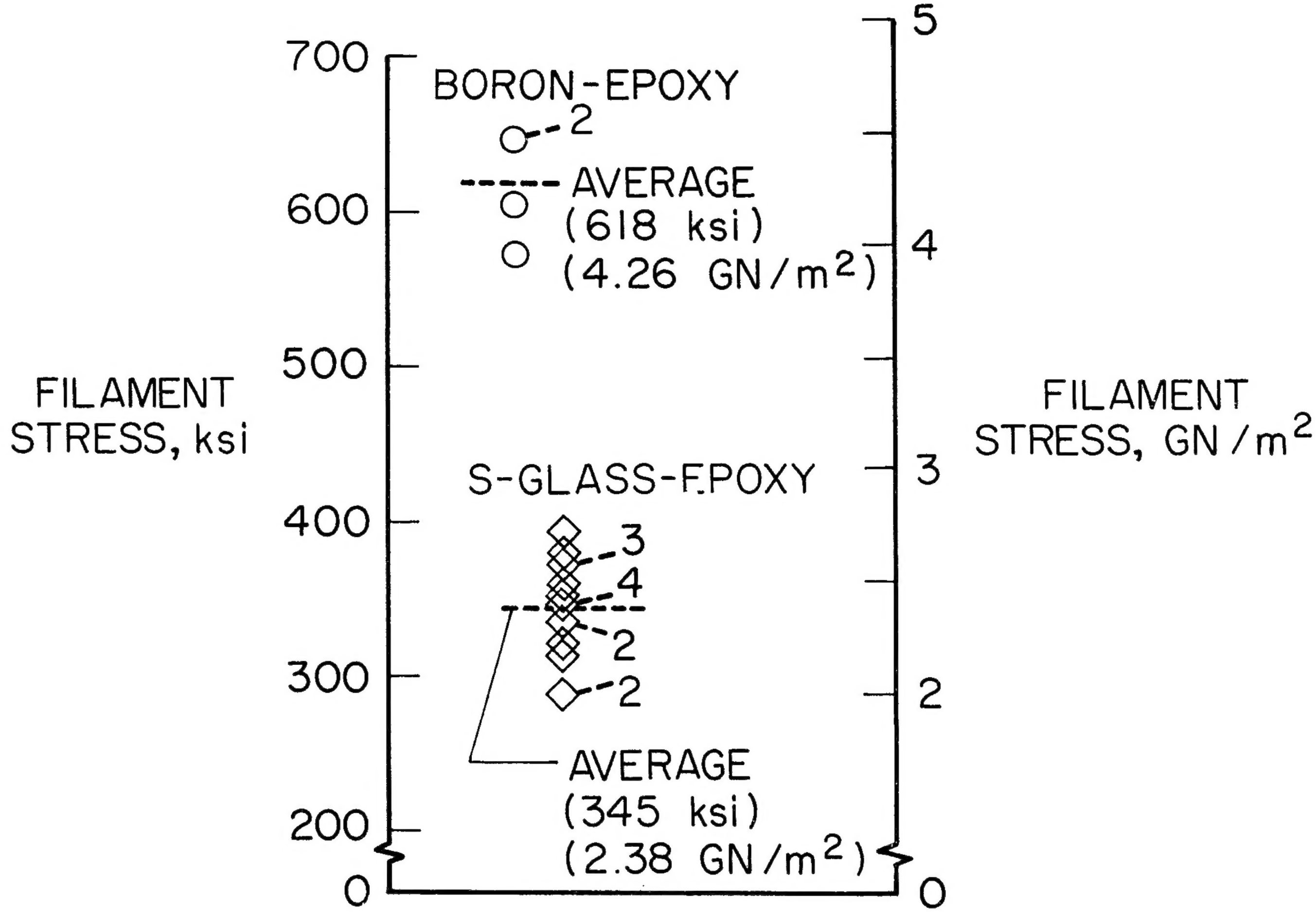

Figure 12.- Results obtained from axial compression tests of short tube specimens.

NASA-Langley, 1968